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Article *in* Journal of the Science of Food and Agriculture · March 2015

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Review

Received: 28 July 2014 Revised: 11 March 2015 Accepted article published: 18 March 2015 Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/jsfa.7176

From raw material to dish: pasta quality step by step

Angelo Sicignano, Rossella Di Monaco,* Paolo Masi and Silvana Cavella

Abstract

Pasta is a traditional Italian cereal-based food that is popular worldwide because of its convenience, versatility, sensory and nutritional value. The aim of this review is to present a step-by-step guide to facilitate the understanding of the most important events that can affect pasta characteristics, directing the reader to the appropriate production steps. Owing to its unique flavor, color, composition and rheological properties, durum wheat semolina is the best raw material for pasta production. Although pasta is traditionally made from only two ingredients, sensory quality and chemical/physical characteristics of the final product may vary greatly. Starting from the same ingredients, there are a lot of different events in each step of pasta production that can result in the development of varieties of pasta with different characteristics. In particular, numerous studies have demonstrated the importance of temperature and humidity conditions of the pasta drying operation as well as the significance of the choice of raw material and operating conditions on pasta quality.
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Keywords: semolina pasta; scanning electron microscopy; drying; microwave; cooking; gluten

INTRODUCTION

In this review the term 'pasta' will be used exclusively for the extruded products made from durum wheat semolina. Pasta is a highly popular cereal-based food product worldwide because of its taste, convenience of use, ease of cooking and storage properties;[1–3] its consumption is recommended by Mediterranean dietary guidelines, where it is considered a fundamental food.[4]

Nowadays eating pasta is perceived as one of the 'healthy options', since it is supremely versatile as a base to a meal and is easy to prepare in a way to satisfy both our notions of 'healthy eating' and our appetite.[5]

Prevalently constituted by carbohydrates (700 g kg^{-1}) and proteins (115 g kg^{-1}),[6] pasta is considered to be a slowly digestible starch food, a nutritional quality ruled by its structure as well as its composition.[7–10] Research has shown that sugars are progressively liberated from pasta during human digestion, lowering postprandial blood glucose and insulin reponse,[11] with possible reduction of esophageal cancer risk.[1] Many studies has focused on the mechanism of starch degradation in cereal products; food structure, porosity[12] and interactions among food components have also been investigated in order to better understand starch behavior during degradation.[13] The release of starch degradation products was found to be slower in pasta than in other cereal-based products. This was mainly attributed to the compact structure of pasta resulting from the extrusion process, which leads to the formation of a very close protein network entrapping starch granules and delaying enzymatic attack[14,15] and to interactions with other components such as dietary fiber.[16]

Good cooking performance of pasta is characterized by high firmness, low bulkiness, absence of stickiness and low cooking loss, characteristics that reflect high cooking and overcooking tolerance.[17] This behavior is strongly related to pasta structure, described as a compact matrix with swollen starch granules entrapped in a coagulated protein network.[18,19] Protein coagulation and starch gelatinization phenomena, and consequently the overall cooking quality of the final product, are greatly affected by the native properties of the raw material and also by the temperature/moisture conditions used during the drying operation,[20] which is the last step before final packaging and represents a crucial point affecting pasta quality, since a lot of modifications of the main components can take place. This step is necessary, since dough moisture must be reduced by up to 125 g kg^{-1} to allow pasta storage at room temperature.[4]

This review is focused on the critical technological points of pasta production that can affect overall pasta quality. Starting from raw material quality, the most important molecular processes and reactions are critically analyzed and consequent structural changes that occur during pasta production are considered.

The flow chart in Fig. 1 shows the main differences between traditional and modern pasta production processes.

GRAIN AND OTHER INGREDIENTS

Evaluation of good pasta-making potential starts from the grain. Aspects of importance include test weight, 1000-kernel weight, physical defects, vitreousness, moisture content, weather damage and grain protein percentage.[21] The most appropriate wheat for

* *Correspondence to: Rossella Di Monaco, Food Science and Technology Unit, Food Science and Agricultural Department, University of Naples – Federico II, Via Università 100, I-80055 Portici (NA), Italy.*
E-mail: rossella.dimonaco@unina.it

Food Science and Agricultural Department, University of Naples – Federico II, Via Università 100, I-80055, Portici, NA, Italy

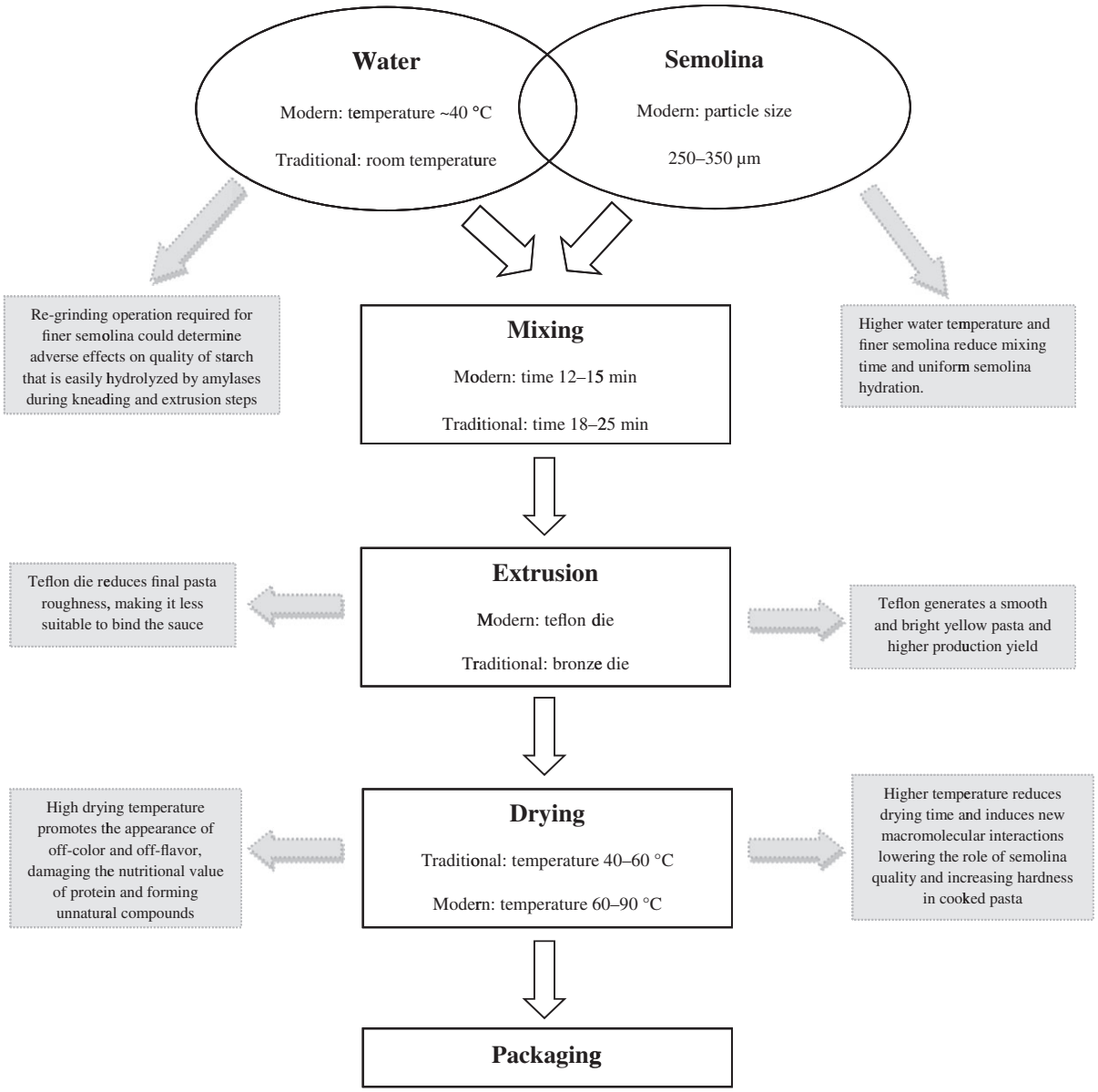
Water
Modern: temperature ~40 °C
Traditional: room temperature
Semolina
Modern: particle size
250–350 µm
Re-grinding operation required for finer semolina could determine adverse effects on quality of starch that is easily hydrolyzed by amylases during kneading and extrusion steps
Mixing
Modern: time 12–15 min
Traditional: time 18–25 min
Higher water temperature and finer semolina reduce mixing time and uniform semolina hydration.
Teflon die reduces final pasta roughness, making it less suitable to bind the sauce
Extrusion
Modern: teflon die
Traditional: bronze die
Teflon generates a smooth and bright yellow pasta and higher production yield
High drying temperature promotes the appearance of off-color and off-flavor, damaging the nutritional value of protein and forming unnatural compounds
Drying
Traditional: temperature 40–60 °C
Modern: temperature 60–90 °C
Higher temperature reduces drying time and induces new macromolecular interactions lowering the role of semolina quality and increasing hardness in cooked pasta
Packaging

Figure 1. Flow chart of traditional and modern pasta production processes. The positive effects of the modern process are listed on the right, while the negative effects are listed on the left.

making pasta products is durum wheat (*Triticum turgidum* ssp *durum*). This is one of the hardest varieties of wheat, and milling it produces coarse particles called semolina, ideal for making pasta. Variation in grain hardness is one of the most important traits determining the end-use quality of wheat. Hard wheat meals are coarser and flow and bolt more easily than soft wheat flour. Grain texture classification is based primarily on either the resistance of kernels to crushing or the particle size distribution of ground grain or flour.[22] It impacts significantly on the milling process, influencing among other things milling yield and particle size. The hardness of wheat is largely controlled by genetic factors but can also be affected by the environment and factors such as moisture, lipid and pentosan contents.[23] The proteins puroindoline a and b are the molecular genetic basis of grain hardness or texture. When both proteins are in their 'functional' wild state, the grain texture is soft; when either of them is altered by mutation or absent, the result is a hard texture. Regarding durum wheat, which lacks puroindolines, the texture is very hard.[22]

Hardness, intense yellow color and nutty taste are the most important features of durum wheat for pasta with good cooking quality, stability to overcooking and unmatchable eating quality.[24] The role of starch in the determination of the rheological characteristics of durum wheat dough is sometimes underestimated in comparison with the role of gluten. Nevertheless, the surface characteristics of starch granules may affect the type of protein–starch interaction and the viscoelastic behavior of pasta.[25]

To improve nutritional quality and/or make special pastas, various ingredients can be added to semolina. In the USA, pasta is enriched with vitamins and minerals.[26] Other examples of materials added to pasta are wheat bran and other fibers used for the purpose of increasing dietary fiber content. Flours of edible legumes, buckwheat, amaranth and lupin and a variety of non-traditional products have been used to reduce the glycemic index or to

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improve the cooking or textural quality of refrigerated, frozen or canned pasta.[26,27] The spread of various allergies and diseases such as celiac disease has helped the development of new types of pasta made exclusively from gluten-free raw materials.

Gluten proteins in grain

Although wheat gluten proteins, which are water-insoluble storage proteins, form only a small part of the endosperm (~7–20%), they constitute 85% of endosperm proteins.[28] Gluten proteins serve as a source of carbon, nitrogen and sulfur for the immature plant.[29] The most abundant amino acid is glutamine, which together with proline and glycine constitutes about 50% of amino acid residues in gluten.[30] Additional characteristics of gluten proteins include a large number of hydrophobic amino acid residues (~35%), while methionine, tryptophan and lysine are the nutritionally limiting amino acids in gluten.[29–31]

According to the protein classification of Osborne,[32] proteins of durum wheat can be fractioned into albumin (soluble in water), globulin (soluble in salt solution), gliadin (extractable in aqueous ethanol solution) and glutenin (soluble in dilute acid). Albumins and globulins are found in lower proportion (20%) than monomeric gliadins and polymeric glutenins (80%). The Osborn partitioning procedure based on protein solubility in different solutions was only one step in the identification of major groups of wheat proteins. Using electrophoresis techniques, it has now been clarified that gliadin and glutenin are two major groups of proteins, each composed of several individual subunits; at present we know that four gliadins (α, β, γ, ω) ranging in molecular weight from approximately 15 to 60 kDa account for about 50% of gluten proteins.[31] The α-, β- and γ-gliadins are known as sulfur-rich and generally range from 25 to 40 kDa. The ω-gliadins are considered to be sulfur-poor and have molecular weights that are approximately twice those of the other gliadins.[31] Meanwhile, polymeric glutenin complexes range from 100 to $>10^7$ Da in molecular weight.[33]

The two main glutenin fractions are low-molecular-weight glutenin subunits (LMW-GS) and high-molecular-weight glutenin subunits (HMW-GS), with molecular weights of about 20–45 and 70–136 kDa respectively, estimated after reduction of intermolecular disulfide bonds.[29,34] The sulfur-poor HMW-GS are constituted by a mixture of periodic and α-helical structures at both termini, with a β-spiral central repetitive region and two to five free cysteine residues.[29] The sulfur-rich LMW-GS are not as well characterized but are thought to consist of an α-helical structure at the C terminal, with irregular β-turns near the N terminal region; one or two free cysteine residues participate in intermolecular disulfide bonds.[34]

The protein matrix entraps starch granules during cooking, thereby conferring pasta its special structure, reducing the loss of solids in the cooking water and thus reducing surface stickiness.[24] Durum wheat with low levels of protein produces extremely fragile pasta with low firmness. High-protein durum wheat allows pasta to swell when cooked, reduces cooking loss and improves texture, with better retention of firmness in overcooking, which is also associated with less stickiness.[35]

Durum wheat breeding programs have continued to make protein and gluten quantity the main objectives owing to their importance in marketing and quality determination of pasta. Relating protein composition to quality requires investigation at different levels. The ratios of glutenin to gliadin and of HMW-GS to LMW-GS are the main factors studied.[24,36]

It is generally accepted that glutenins confer elasticity and gliadins are responsible for the viscosity and extensibility of gluten, the interactions between these two protein fractions determining the ultimate gluten quality of an individual cultivar.[37] It is also accepted that the glutenin fraction is still the main one responsible for gluten strength.[38] Both HMW and LMW glutenins, but mainly the latter, have a great influence on gluten strength and on the pasta-making quality of durum wheat,[39] stressing the need to obtain cultivars with optimal HMW and LMW glutenin combinations to boost gluten quality.

In particular, LMW glutenins contain a specific number and distribution of cysteine residues that confer the ability to form intermolecular disulfide bonds either with other LMW glutenins or with HMW glutenins, thus contributing to the formation of glutenin polymers. Conversely, the number and distribution of cysteine residues in gliadins allows them to form only intramolecular disulfide bonds, with the result that they are monomeric components of gluten.[34]

Several models have been suggested over the years to describe the gluten network structure. The current widely recognized model was proposed by Shewry *et al.*[40] in 2001. In this model, HMW-GS constitute the main backbone via head-to-tail disulfide crosslinks, with a limited extent of lateral disulfide bonding between HMW-GS chains. LMW-GS participate by acting as chain connectors or terminators as a function of the number of free sulfhydryl groups available for disulfide bond formation. Gliadins interact non-covalently with HMW-GS chains, conferring a modulatory role in terms of glutenin elasticity.[41]

The ratio of polymeric glutenin to monomeric gliadin can be directly related to the balance between tenacity and extensibility. The effect of variation in the ratio of HMW-GS to LMW-GS is less clear.[36] One important aspect to define protein quality is gluten strength, an indicator of gluten viscosity and elasticity. It is accepted that weak and inelastic gluten produces pasta with low cooking quality, but how much strength is optimal is not known.

A strategy commonly employed by millers in Italy to increase gluten strength in weak semolina is blending with a high-strength semolina, which enhances pasta texture. It is thought that gluten strength is related to the balance between viscosity and elasticity.[29] Generally, it is accepted that semolina from extra strong durum varieties produces firmer pasta; as a result, gluten strength has become one of the important parameters determining the commercial value of semolina.

Starch and minor components

Wheat starch is composed of granules of two different sizes: small spherical B-type granules (average diameter 1–10 μm) and larger lenticular A-type granules (average diameter 15–40 μm).[42] The structure and amylose content of starch granules were found to influence pasta characteristics. Spaghetti made from semolina samples with 32–44% B granules exhibited higher cooked firmness and lower stickiness compared with the control sample (22.7% B granules). Pasta cooking loss decreased with elevated B granule content, which is a positive feature. A larger proportion of small-size granules allows a more uniform distribution of protein during kneading in comparison with large-size granules; this can affect the loss of amylose, reducing cooking loss.[43]

Lipids, despite accounting for only 10–30 g kg^{-1} (dry matter) of the grain, are an important component of wheat. There are both starch-bound and non-starch lipids in semolina. Starch-bound lipids interact with the amylose helix and exist as amylose inclusion complexes in starch granules.[44] Non-starch lipids are all other lipids in the grain. They are further divided into free (soluble in non-polar solvents) and bound (soluble in cold polar solvent

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mixtures) components. Free lipids represent 64% of total lipids.[24] During the dough mixing process, they interact with proteins to provide a beneficial influence on gluten strength. Sissons[24] found that removal of total lipids from semolina had detrimental effects on pasta quality, such as an increase in stickiness, whereas, with addition of lipids, samples showed lower stickiness.

Lipids are also important in determining the color of pasta due to pigments and lipoxygenase (LOX). Yellow color is mainly determined by the amount of carotenoid pigments in grain resulting from the balance between pigment synthesis and pigment degradation by LOX.[45] Semolina LOX activity was found to be highly correlated with the extent of decrease in pigments,[24] and the reduction of LOX activity during pasta processing is of interest for technological and commercial purposes. LOX reaction could be inhibited by β-carotene, and a lower degree of semolina bleaching was observed in samples with higher carotenoid content,[46] so it is suggested that a high carotenoid content of semolina is desirable to impart a better color, preventing carotenoid bleaching during pasta processing. The presence of other enzymes such as amylases and polyphenol oxidase (PPO) in wheat is another important factor that can affect pasta quality. Amylase activity (AA) is lower in semolina than in whole kernel, because amylases are mainly present in the outer layer of the kernel, which is discarded during milling. In the industrial milling process, in order to increase the extraction rate, some of these fractions are added to 'core streams' and at the same time increase the potential AA in semolina and hence the amount of reducing sugar and the extent of Maillard reaction (MR) that potentially will take place during pasta drying.[20]

Meanwhile, PPO catalyzes the oxidation of a large number of phenols present in the grain. This enzyme resides mainly in the pericarp and grain layers and can cause enzymatic browning in food material through initial oxidation of phenols to quinones that readily undergo self-polymerization or condensation with amino acids or proteins via their amino groups to form complex brown polymers.[47] Since the source of PPO is the bran layers, excess bran in the semolina arising from poor purification could produce brownness in the pasta.[47]

SEMOLINA PARTICLE SIZE AND MIXING OPERATION

Durum wheat milling is a complex procedure of progressive grinding and sieving. The very hard durum grain must be tempered to the right moisture content (100–170 g kg^{-1}) before grinding it on corrugated break rolls.[48] The grinding step is aimed to break up wheat kernels and to separate the endosperm from the bran, preserving grain quality. Semolina possesses irregularly shaped particles with variable sizes characterized by sharp edges. When observed by scanning electron microscopy (SEM), semolina shows a compact structure, with few visible starch granules entrapped in a protein matrix.[49] At room temperature, semolina proteins and starch behave as a glassy material. After the addition of some water, proteins become rubbery and elastic, becoming able to form strands and sheets via intermolecular bonds during mixing. The gluten network formed helps to trap the starch granules in pasta and hold the pasta shape during cooking.[24]

Semolina particle size is a key quality factor in pasta making. Semolina used for pasta processing typically ranges in particle size from 550 to 150 μm.[20,26,50] Pasta manufacturers choose the particle size distribution of semolina according to the desired final product characteristics and the production requirements. The underlying principle is that the more even the particle size, the more uniform is the hydration of semolina during mixing. Hydration of semolina with a wide range of particle sizes results in over-hydration of the finer fraction and under-hydration of the coarser fraction. Such non-uniform hydration will adversely affect dough development and pasta quality.[26] There is, however, no ideal granulometry, as this requirement refers to the method of production used by the pasta maker. The tradition was for larger particle size (mainly consisting of particles in the size range 250–350 μm), but modern pasta-making plants require finer semolina (<300 μm) that hydrates quicker. Finer, floury particles were associated with poor-quality pasta; however, if milled correctly, a particle size range akin to flour can be used successfully, giving good-quality pasta at increased milling yield and faster mixing speeds.[51] Modern high-speed extrusion processes are characterized by limited dough residence time, and finer semolina is particularly suitable since it avoids the appearance of white spots due to poor hydration of the particles; it confers to pasta a highly homogeneous color with higher yellow color saturation than coarser semolina.[47]

Differently from the modern high-speed/high-temperature plants, small manufacturers usually prefer the traditional way of producing pasta using semolina of larger particle size. Although coarser semolina requires longer hydration times, it suffers less starch damage. The re-grinding operation required for fine semolina making could have adverse effects on the quality of starch that is easily hydrolyzed by amylases. During the kneading and extrusion steps, the pH (slightly acidic) and temperature (40–50 °C) conditions are optimal for amylases and result in an increase in reducing sugar content from semolina mixing to dough extrusion, thereby accelerating MR during drying, with adverse effects on both color (browning) and nutritional value (loss of lysine).[52]

The damage to starch also increases granule swelling and solute dispersion from starch granules during cooking.[53] Finally, starch damage reduces the gelatinization enthalpy of wheat, which affects the cooking quality of pasta from fine semolina.[54]

The right amount of water to be added to semolina generally ranges from 250 to 340 g kg^{-1} depending on the initial moisture content and resulting pasta shape.[54] Usually, for extruded spaghetti, 265 g of water is added to 1 kg of semolina to obtain a dough with 320 g kg^{-1} water content. The mixing stage is performed under vacuum to remove air from the dough and avoid air bubbles in the pasta. During the mixing operation, heterogeneous hydrated pea-sized lumps (2–3 cm diameter) are formed in the mixing chamber.[55] The right mixing time depends mainly on the semolina particle size; the absence of non-hydrated particles in the final dough is very important, since they could induce defects in the pasta. The water temperature is another factor that influences the time of kneading. Generally, in Italy, high-speed plants use conditioned water at temperatures up to 40 °C, while small manufacturers use unconditioned water. The time of kneading may vary from 12 to 25 min depending on the semolina particle size and water temperature. As water absorption takes place below 50 °C, starch granules show no important structural changes,[56] and no indication of gluten network formation is apparent,[57] due also to the limited hydration level and low energy input.[58]

DIE MATERIAL AND EXTRUSION OPERATION

The wet mix passes into the vacuum screw and to the extruder, forming a dough, and the application of mechanical work causes protein aggregation and gluten network formation.[24] The extrusion step is conducted at temperatures lower than those causing

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insolubilization of proteins. When the extrusion temperature exceeds 50 °C, the starch granules begin to undergo abnormal swelling, and protein coagulation occurs.[20] However, in the extrusion worm, pressure builds up and the dough temperature can rise locally; structural transformations are the result of both shear stress and thermal energy involved during extrusion.[59] The screw rotation pushes the dough toward the die, where it takes its final shape.[55] The extrusion pressure is essential to give the product the necessary texture to preserve its shape during cooking;[58] as the dough progresses through the screw, the pressure increases. The pressure at the die is generally around 10 MPa (extruding and drying the pasta); however, depending on the die material, pasta final shape and plant type, it may be up 13–14 MPa. Compared with semolina, pasta freshly extruded at low temperature (35–40 °C) does not differ significantly ($P < 0.05$) in protein solubility.

Concerning the starch fraction, mechanical forces concomitant with a local increase in temperature (>60 °C) can lead to moderate damage to starch granules. Differential scanning calorimetry (DSC) measurements show a higher gelatinization enthalpy of semolina compared with extruded pasta,[56] which could be explained by the presence of some gelatinized and/or damaged starch granules in pasta. The high pressure occurring in dough extrusion was found to promote amylase inactivation, and only a small further increase in reducing sugar amount was observed during the subsequent drying step.[20]

Freshly extruded pasta observed by SEM possesses a compact internal structure with starch granules of irregular size and shape deeply embedded in a protein matrix and aligned along the direction of flow.[60]

Other important variables that can affect pasta characteristics are associated with the use of die inserts made from different materials. The most widely used die inserts are made from Teflon or bronze. With regard to the appearance of the pasta surface, Teflon gives a smooth and bright yellow appearance to the product, whereas bronze gives a rough surface to the pasta. The use of bronze dies has the disadvantages of lower production yield of the press and faster wear of the die insert,[26] which are the main reasons promoting the use of Teflon in high-speed plants.

Fresh pasta extruded with a bronze die has higher water content and larger diameter and expands more than fresh pasta extruded with a Teflon die. These results indicate that the use of different die materials would lead to different matrix structures.[61] Using the same raw material and adopting the same process steps, bronze die samples appeared more fragile than Teflon ones: statistically lower forces are required for breaking samples prepared with both fine and coarse semolina.[62]

The rough surface of bronze inserts produces large pores on the pasta surface, with a porous gradient that gradually decreases toward the center of the product;[63] the higher porosity is probably a consequence of the rough surface of the pasta, resulting in a decrease in apparent density. The higher volumetric fraction of air present in the matrix of bronze-extruded pasta can explain the lower breaking strength that has been associated with it.[62]

As a result of the higher porosity, a bronze die induces an increase in effective moisture diffusivity compared with a Teflon die, while the equilibrium moisture content is not affected.[61] From the measured effective moisture diffusivity and equilibrium moisture content, using a model derived from Fick's law, the time required to dry a 2.5 mm pasta from 500 to 200 g water kg^{-1} dry matter at 80 °C would be 97 ± 2 min for Teflon die extrusion and 71 ± 2 min for bronze die extrusion.[64]

Ultrastructure imaging magnifies the differences in smoothness between Teflon- and bronze-extruded spaghetti already evidenced by visual inspection. SEM observations show that Teflon-extruded spaghetti has a very compact structure in which the starch granules and protein matrix are fused together and are no longer clearly distinguishable, while the surface of bronze-extruded spaghetti is characterized by the presence of gluten strands that only partially cover the starch granules, thus leaving many small cavities between them.[62] The product roughness makes bronze die pasta more suitable to bind the sauce than Teflon die pasta, but at the same time facilitates insect attack. Clinging to the product, insects gnaw its surface and make small holes in which to lay their eggs, helped by the reduced mechanical strength of the bronze-extruded material.[65]

DRYING OPERATION

The assessment of internal water profiles during pasta drying is a critical point for tailoring pasta properties, minimizing the possibility of crack formation and achieving uniform glass transition conditions.[66] Since the 1970s, technological improvements have induced an increase in drying temperatures of pasta from low (LT, 40–60 °C) to high (HT, 60–84 °C) and very high (VHT, >84 °C) temperatures, thereby reducing drying times and improving hygienic standards. Moreover, the use of HT is also beneficial for the overall cooking performance of pasta.[67] HT/short-time (ST) drying conditions were first used commercially in 1974.[51] Since then, there has been a continuous increase up to 90 °C and even higher, allowing pasta to be dried within 2–3 h.[51]

Weegels *et al.*[68] studied the reactivity of gluten and found that major changes occurred when gluten with a moisture content of 250–300 g kg^{-1} was heated to 80 °C. A decrease in protein solubility was found, mainly due to the glutenin fraction. This situation can be compared to the conditions applied during pasta drying at HT. Heating to 90 °C causes conformational changes in glutenins, exposing previously unavailable areas containing free sulfhydryl (SH) groups, followed by polymerization via oxidation of most SH groups.[69] Above 90 °C, the remaining free SH groups of glutenins can induce covalent linkages with gliadins through a heat-induced SH–disulfide exchange mechanism catalyzed by SH groups. It is probable that conformational changes in gluten proteins due to HT are necessary for gliadin–glutenin crosslinking.[70]

Durum wheat semolina is characterized by a high fraction of sodium dodecyl sulfate (SDS)-soluble proteins (80–83%) and a low fraction of dithioerythritol (DTE)-soluble proteins, while dried pasta shows higher protein aggregation, as indicated by a decrease in SDS-soluble proteins in favor of DTE-soluble proteins (19–17%), and no traces of unextractable proteins.[54] This phenomenon suggests a rise in protein aggregation through the formation of additional disulfide bonds with increasing drying temperature, particularly when VHT (≥90 °C) is applied to low-moisture (LM) pasta.[71]

According to various authors, higher drying temperatures generally improve pasta cooking performance even though such temperatures applied to high-moisture (HM) pasta can cause excessive swelling of starch granules with consequent breakdown of the protein network and a decrease in overall cooking performance.[72] The best results are obtained using a preliminary low drying temperature in the first step to reduce pasta moisture, followed by a high drying temperature.[73] However, HT drying promotes extensive heat damage in pasta, correlated with the appearance of off-color and off flavor,[74] reducing the nutritional value of protein[75]

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and forming unnatural compounds.[76] A high drying temperature induces new macromolecular interactions, lowering the role of semolina quality in pasta cooking performance;[77] if pasta is dried at HT, the quality of the raw material can be considered a non-critical parameter.[78]

Zhang *et al.*[79] demonstrated that the moisture distribution in pasta depends on the drying temperature and that pasta dried below the gelatinization temperature absorbs water better. Pasta dried at higher temperature (≥70 °C) absorbs less water in the inner part; conversely, pasta dried at lower temperature (≤50 °C) behaves in the opposite way. When the drying temperature is above the gelatinization temperature, the dependence of the moisture distribution on the drying temperature is no longer found. This phenomenon can be attributed to starch granules arising in the surface of pasta dried at higher temperature. The higher drying temperature allows starch granule gelatinization, preventing the diffusion of water to the inside. LT-dried pasta shows higher water absorption than HT-dried pasta under any cooking conditions.[80] On increasing the drying temperature, the swelling of starch granules is hindered by the formation of a more aggregated gluten network during the process.[19] Moreover, HT drying increases the hydrophobic properties of the gluten network; higher levels of amylose–lipid complexes are observed with higher drying temperatures. The increase in amylose–lipid complexes contributes to lowering of the water absorption.[80] It has been demonstrated that the drying temperature also influences pasta digestibility *in vitro*. Compared with low drying temperature, the application of VHT/LM drying decreases starch and protein digestibility *in vitro*, with a greater effect on the latter;[55] this finding could be explained by the presence of highly aggregated proteins stabilized by covalent protein as gliadin–glutenin aggregates and MR products.[55] Indeed, the development of MR compounds occurs during pasta drying, especially at HT and VHT.[81]

The application of HT treatments enables an improvement in pasta cooking properties, with an increase in plant productivity and a reduction in microbial contamination;[82] however, the development of uncontrolled reactions such as MR can be induced too.[76] During HT/LM drying, pasta reaches a water activity (a_w) value of 0.70–0.80, which is recognized as optimal for MR.[83] Pagani *et al.*[84] found the highest level of MR products in samples manufactured by high extraction rate milling and using semolina of small size, drying at temperature up to 75 °C when pasta presents low moisture. The early stage of MR may affect the nutritional value of pasta protein, reducing nutritionally available lysine and methionine and inducing excessive browning due to the formation of colored compounds and the loss of carotenoids.[85] In the advanced stages of MR can also occur the formation of flavor compounds from free sugars[76] as well as important changes in flavor composition resulting from Strecker degradation[86] and thermal oxidation of lipid components.[87] In Italy, traditional LT drying is mainly used by small producers to produce regional and traditional shapes. Generally, traditional pasta shapes are thicker than pasta shapes from large-scale production, which require more subtle forms for drying at HT. The use of HT to dry thicker shapes may cause microscopic fractures that will result in pasta of poor cooking quality.

Anyway, in recent years, research on pasta drying continues to move in the direction of time reduction and productivity increase. It would seem that the use of microwaves might meet these expectations, also reducing the size of dryer plant.

Several advantages were highlighted for the first time after the joint work of a pasta processor in Canada (Lipton) and an equipment manufacturer in the USA (Cryodry), who were engaged to adapt a microwave stage on an existing industrial conventional process. In an article by Maurer *et al.*,[88] several factors to consider when evaluating the economics of the process compared with conventional microwave are described.

Compared with conventional methods of heating whereby heat is transported from the surface to the center, heating of foods exposed to a microwave field is 10–20 times faster.[89] In comparison with conventional drying, the use of microwave-assisted hot air drying has two main advantages: higher production speed and lower space utilization. Berteli and Marsaioli[90] found that a combined microwave/hot air rotary dryer reduced the drying time more than tenfold compared with the conventional drying process without harming the appearance of the pasta, resulting in a final product without fissures. The physical and textural properties of pasta dried by combined microwave/hot air were reported to be equal to or better than those of pasta dried conventionally.[91] Generally, an increase in pasta firmness and a reduction in cooking loss are observed with microwave application. The shorter drying time is due to the additional energy input and rapid heat penetration of microwaves. At present, no industrial plants use this drying method; it is necessary to perform a more precise economic analysis considering the potential advantages/disadvantages of microwave drying compared with traditional techniques in order to evaluate the costs/benefits of this potential innovation in pasta drying.

COOKING PROCEDURE

Traditional cooking

During the cooking time, water increases in concentration at the pasta surface and moves toward internal regions, creating a sort of discontinuity in concentration that progressively disappears as the overcooking phase is neared. As the cooking time proceeds, lots of structural transformations occur, dependent on those that occurred in the previous processing steps; the final pasta structure is the result of all changes occurring during pasta making and is mainly affected by the starch and protein fractions.[55]

Modification of process parameters also impacts pasta nutritional properties; indeed, as discussed below, the nutritional properties of pasta are closely linked to its structure.[11,13]

In traditional consuming countries, consumers regard cooking performance as the main attribute related to pasta quality, followed by sauce-binding capability and yellow color, while stickiness is considered the main defect.[92]

Starch gelatinization and protein coagulation are the main events that occur during the cooking time. Protein coagulation and interaction lead to the formation of a continuous and strengthened network that traps starch granules, while the latter, by swelling and gelatinization, occlude all free interspaces, giving pasta its special structure.

A decrease in protein solubility in SDS is observed during cooking. Depending on the previous drying temperature applied, the loss of protein solubility during the cooking step can be more or less accentuated. If one compares the solubility of proteins in pasta submitted to different drying temperatures, it appears that higher drying temperature leads to less marked changes in pasta protein solubility during cooking, because most of the proteins have been aggregated during the drying step.[55] Starch and protein transformations occur in a similar range of temperature and moisture conditions (proteins react at slightly lower moisture level);[93] both components compete for water, and the swelling of starch granules is antagonistic to protein network formation during the cooking

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step.[94] When the protein network is not strong and elastic, the starch swells and gelatinizes before protein coagulation; amylose goes mainly into the cooking water and amylopectin fragments move to the pasta surface, thus reducing pasta cooking quality. On the contrary, when protein interactions prevail, starch granules, which hydrate slowly, are trapped within the protein network, and the resulting cooked pasta will be firm with no stickiness or clumpiness.[20]

Both transformations are mediated by water uptake during cooking. As the cooking time proceeds, the water absorption rate depends on the ability of water to diffuse through the matrix and on the melting kinetics of domains.[15] Water acts as a plasticizer and increases polymer mobility, penetrating toward the center as the cooking time proceeds. The lower moisture content in the inner parts of pasta generates greater competition for water between proteins and starch, leading water to being unevenly distributed among components.[55] Higher hydration of proteins locally may cause protein network formation before starch swelling.

When pasta is dried at LT, its cooking quality is mainly a function of protein content and gluten properties. In the case of HT drying, only the amount of protein assumes a primary role. The gluten coagulation before cooking induced by drying temperatures higher than 60 °C reduces the need for a strong gluten network in semolina.[7] Various authors have described the role of drying temperature in determining pasta cooking quality, almost regardless of protein content;[3,17] there is general agreement that LT-dried pasta gives a lower cooking performance compared with HT-dried pasta.

Observing the surface of cooked pasta by SEM, proteins and starch are no longer distinguishable from one another, forming a thin film with some small cracks and open areas.[95] Moving the observation inward, the structure of cooked pasta can be divided into three different concentric regions: an external region, an intermediate region and a central region.[71,95] In the external region, starch granules are extensively deformed and swollen and it is difficult to differentiate them from proteins by SEM observation.[14,95] The intermediate and central regions of cooked pasta are clearly distinguished from the external region; the intermediate region is characterized by partly swollen granules embedded in a dense protein network,[14,95] while the central region shows low starch granule swelling with a limited degree of gelatinization owing to limited water absorption.[18]

Microwave cooking

Recently, in order to reduce cooking times and automate the cooking process, the use of microwave cooking (MWC) as an alternative to traditional cooking (TRC) of pasta has been proposed. Using a sensory panel of trained judges, no differences were observed between traditionally cooked (TRC) pasta and microwave-cooked (MWC) pasta except in yellow color intensity.[96] As the cooking time proceeds, MWC pasta shows a lower weight increase kinetic than TRC pasta, with an initial diffusion-like step followed by a linear increase in weight. At the same level of water uptake, MWC pasta shows a significantly higher gel degree and lower firmness than TRC pasta. A chemical method showed rates of gelatinization of 13 and 16.1% for TRC pasta and MWC pasta respectively, while the corresponding values from DSC measurement were 96.2 and 99.8%; by SEM observation, MWC pasta shows a morphological modification of starch granules, which take the shape of a flattened disk.[96] In accordance with Cocci *et al.*,[96] at the same weight increase we observed greater morphological modification of the

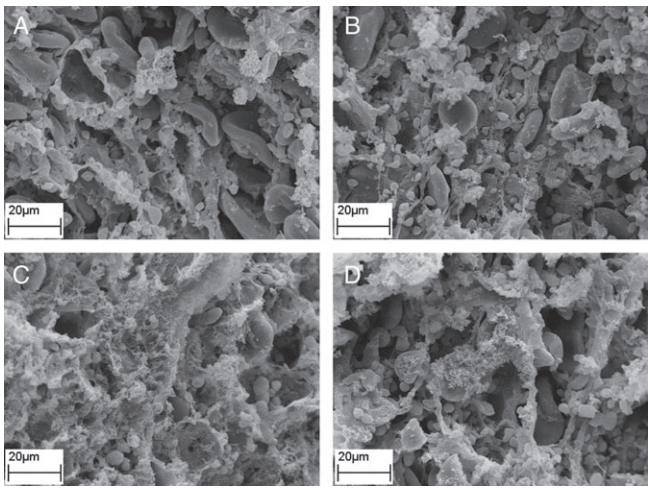

Figure 2. SEM images of inner surface of (A) microwave-cooked (MWC) and (B) traditional-cooked (TRC) pasta and outer surface of (C) MWC and (D) TRC pasta.

starch granules of MWC pasta (Fig. 2A) compared with those of TRC pasta, where the flattened disk shape was less expressed (Fig.2B). The higher extent of gelatinization is probably due to the effect of dielectric heating on the pasta's inner polar molecules during MWC; microwaves reach the inner pasta layer, affecting the temperature profile inside the food.[96]

Observed by SEM, the external surface of MWC pasta reveals a more compact gluten network (Fig. 2C) than that of TRC pasta (Fig. 2D). TRC pasta shows the typical honeycomb-like network observed by others.[96]

Microwave application could induce higher protein denaturation and thus generate a more compact gluten network.[91] MWC gives pasta better color retention, higher gel degree, a more compact gluten network and lower cooking loss. Considering that chemical/physical differences revealed by instrumental analyses are not sensorily perceived and that MWC could reduce preparation time and allow automation of the cooking process, this innovative way to cook pasta could be regarded as a good alternative to TRC.[96]

CONCLUSION

The present paper provides some insights into the pasta production process. Experimental investigations on pasta production were reviewed in order to analyze the variables involved in production and preparation steps with respect to the qualitative characteristics of the pasta at the time of its consumption. Depending on the desired performance and quality standards, manufacturers can choose between different alternatives the way to conduct the production process. Starting from the same raw material, the particle size of the semolina may affect the gluten index, color and hardness of pasta. Other effects can be achieved by the choice of die material to influence the extrusion speed and porosity of pasta. As noted by several authors, the drying operation has the greatest effect on the final product by modifying the structural, chemical/physical and sensory characteristics and *in vitro* digestibility of pasta. High drying temperatures promote the formation of a stronger protein network, thereby improving hardness, cohesiveness, resilience and springiness. On the other hand, low temperatures increase pasta digestibility and yield after cooking by enhancing the ability to absorb water. However, the

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best results are obtained by using a preliminary low drying temperature in the first step to reduce pasta moisture, followed by a high drying temperature. The use of combined microwave/hot air drying seems to be a viable alternative to the classical method in order to increase the speed of pasta production. It would therefore be interesting to conduct a more thorough analysis on the chemical/physical characteristics and complement this with a sensory evaluation in order to better define the relationship between economic benefits and quality of the final product. Considering the interesting results obtained by microwave cooking, it would also be interesting to carry out studies on new alternative cooking methods that might be faster and cost- and/or time-saving with respect to the traditional way. Furthermore, little is known about how pasta shape can affect its characteristics. Aravind *et al.*[97] found that pasta size and shape affected *in vitro* starch digestion by changing the surface/volume ratio; it would also be interesting to know how they can change pasta cooking performance and sensory properties.

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